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New seismic events identified in the Apollo lunar data by application of a Hidden Markov Model

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1. Introduction

The Apollo astronauts installed seismic stations on the Moon during Apollo missions 11, 12, 14, 15 and 16. The stations consisted of a three-component long-period seismometer (eigenperiod 15 s) and a vertical short-period sensor (eigenperiod 1 s). Until today, the Apollo seismic network provides the only confirmed recordings of seismic events from any extraterrestrial. The recorded event waveforms differ significantly from what had been expected based on Earth data, mainly by their long duration body wave codas caused by strong near-surface scattering and weak attenuation due to lack of fluids. The main lunar event types are deep moonquakes, impacts, and the rare shallow moonquakes.

Digital data from the Apollo stations posed a huge challenge to the available processing equipment when they first arrived on Earth, and event detection and arrival time reading was orginally done by visual inspection of data at a reduced temporal resolution. Automatic detection schemes were considered too unreliable or time-consuming at that time. Later re-analysis mainly focussed on deep moonquakes, since they are the most abundant events and occur in spatial clusters of high waveform similarity which allows the use of cross-correlation techniques [6, 2].

These techniques might actually not be ideal for the general use in planetary seismology, though, as they require an extensive set of waveform templates, work best for networks, and might encounter problems if waveform similarity between different events is low. In planetary seismology, waveforms and event types are a priori unknown, missions likely consist of a single seismic station that needs to cover a whole planet, and events might be sparse, but detection and classification should start as soon as possible after deployment. Besides, like for NASA's 2016 InSight mission to Mars, continuous seismic data might only be available at a reduced rate, with higher rate data only available by request for a very limited time after the original downlink [1]. Under these circumstances, a recently introduced event detector and classifier based on Hidden Markov Models that works on continuous single-station data with minimum prior information could be an alternative [4, 3]. We test this algorithm on the data of Apollo station 16. Previously, it had only been applied to broad-band, regional terrestrial data, with events of about one minute duration at high sampling rates and recording dynamics. In all of these aspects, the Apollo data are significantly different.

2. Results

We applied the classifier to both long-period and short-period data streams from April, 1972 to June, 1975. In total, 80% of all events of sufficient quality listed in the Long Period Event Catalog (LPEC) [5] are found, and 70% classified correctly. The false alarm rate is about 20%, mainly determined by deep moonquakes that make up the majority of the data set: For impacts, the false alarm rate is only 6%, and for shallow moonquakes, zero. These results are based on just a single prototype event per event class, which is used to learn the characteristic features of this class. We found that the choice of the prototype deep moonquake, which belongs to cluster A20, does not lead to a preferential detection of events from this cluster. Rather, events from other clusters, notable one located on the farside, are detected with an equal reliability.

Previously unclassified events have the lowest detection rate (58%), which is not surprising: If visual comparison had shown their waveforms to be very similar to any of the known event types, they would have been classified accordingly. Still, we are able to newly classify 35 of these events as deep moonquakes, and 15 as impacts. Events which are detected on both short-period and long-period data streams are also classified consistently.

Besides, we find more than 200 new events not listed in the LPEC. 150 of these events are deep moonquakes, and more than half of them belong to clusters newly identified within these data. Fig. 1 shows the largest of these new clusters, containing 8 events. The newly identified deep moonquakes also show the known temporal pattern in their occurence, related to tidal stresses in the Sun-Earth-Moon system. Newly detected deep moonquakes preferential occur in the later part of the data set, 400 days and more after the installation of station Apollo 16. This observation correlates with a drop in the overall number of deep moonquakes listed in the LPEC by a factor of 4 between the first 100 days after the installation of station 16 to a year or more later. The occurence of newly detected impacts, which are mainly small, close events detected on the short-period component, correlate with known meteorite showers as found by [7].

No unambiguous detections of new shallow moonquakes were made. We tested the ability of the classifier to identify shallow moonquakes as a new, unknown event class if they were not included in the training, assuming that rare events might be unknown at the beginning of a recording period. Identification appears possible based on low values for both noise and event probabilities on the short-period channel, similar to the example in [4].

3. Figures

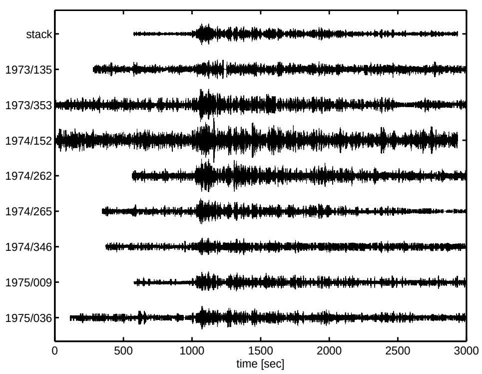

Figure 1: LPY components of a cluster of newly discovered deep moonquakes.

4. Summary and Conclusions

We used a Hidden Markov Model based event detector and classifier on the seismic data of Apollo station 16. It is sufficient to provide a single example waveform of each common event type (deep moonquake, impact, shallow moonquake) for the detector to work, which is a huge advantage over cross-correlation algorithms. The algorithm has proven to work satisfactory and reliably for this rather complex data set, surprisingly also leading to new discoveries in an already well-worked catalog almost 40 years after the end of seismic data transmission from the Moon. It could thus potentially also be useful for future seismometer missions to other planets.

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